Wall-modeled Large Eddy Simulation of Flow Past a Wall-Mounted Hump

Prahladh S. Iyer
National Institute of Aerospace, Hampton, VA

Mujeeb R. Malik
NASA Langley Research Center, Hampton, VA

FD-03: Turbulence Modeling 1: LES, DNS, Hybrid LES/RANS

Monday, June 13^{th} 2016, 10:30 am

Motivation

Boeing 787 Dreamliner[1]

- Most RANS models work reasonably well for attached flows, but do not accurately predict flows involving separation.
- High fidelity DNS/ LES infeasible for realistic high *Re* encountered in flight.

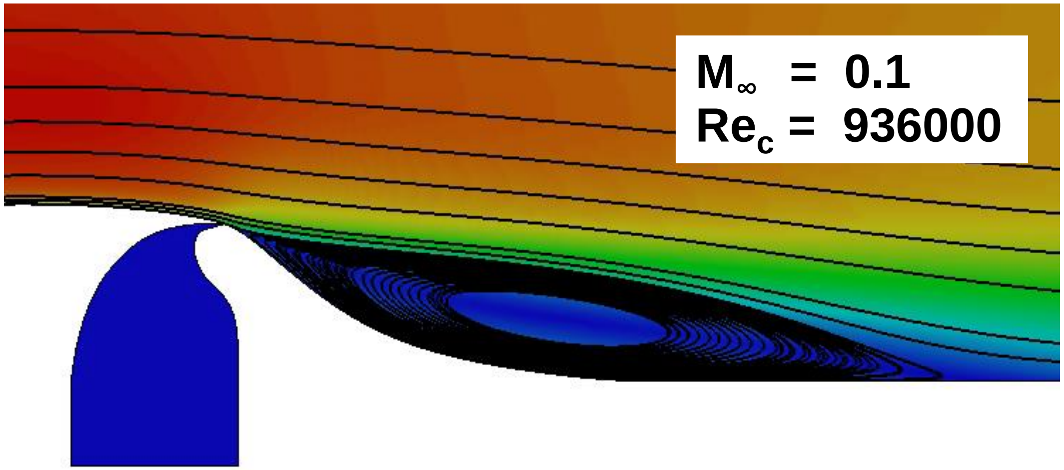
DNS	LES	WMLES
$Re_{Lx}^{37/14}$	$Re_{Lx}^{13/7}$	Re_{Lx}

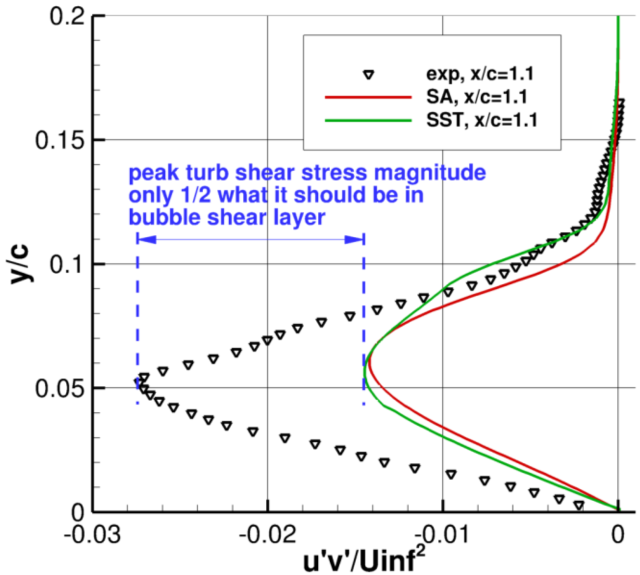
Choi & Moin[2] grid estimate for flat plate turbulent boundary layer.

- **Wall-Modeled LES (WMLES) and hybrid RANS-LES** methods show good promise for high *Re* complex turbulent flows.

[1] Figure taken from : https://en.wikipedia.org/wiki/Boeing_787_Dreamliner
[2] Choi, H., & Moin, P. (2012). Grid-point requirements for large eddy simulation: Chapman's estimates revisited. *Physics of Fluids (1994-present)*, *24*(1), 011702.

Wall-mounted hump geometry[1]



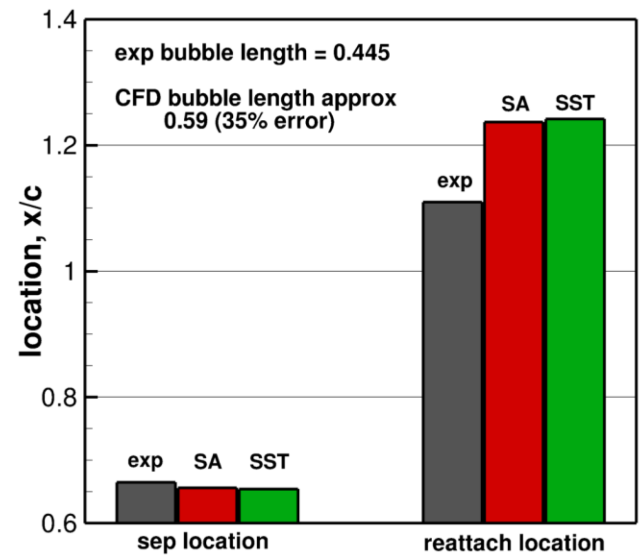


- Standard test case for **Revolutionary Computational Aerosciences (RCA)** under **Transformational Tools & Technologies (TTT)** Project.

- Detailed experimental data available for validation.

- Part of **NASA CFDVAL2004** workshop and **NASA Turbulence Modeling Resource** webpage.

- Up to **35% error in bubble length for** most **RANS** models.

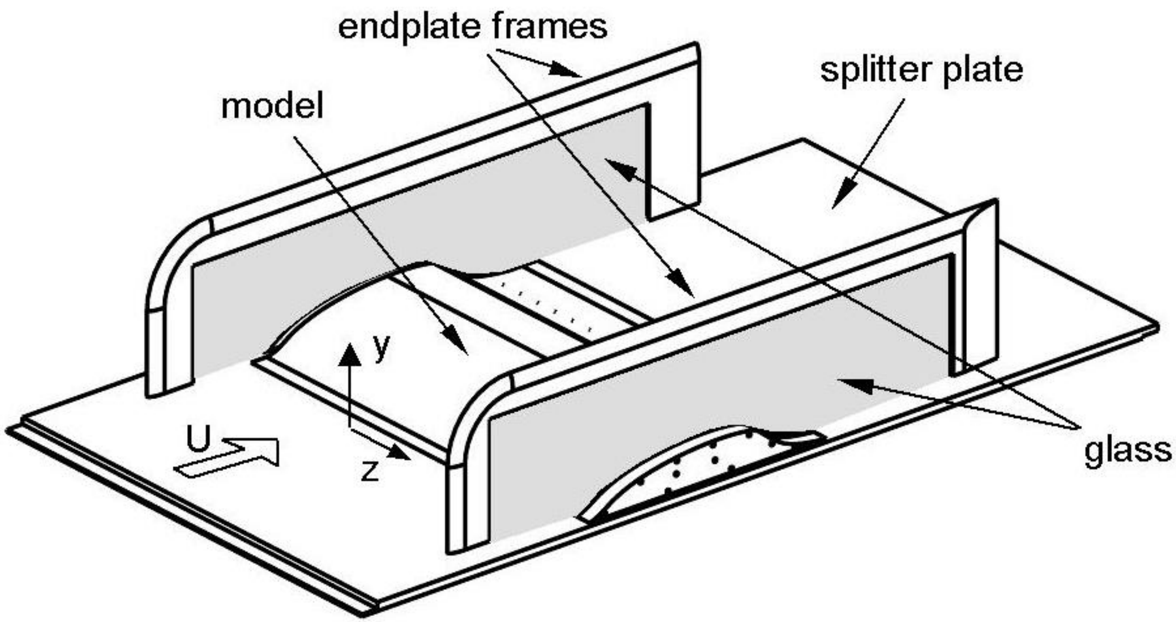


[1] Figures taken from : http://turbmodels.larc.nasa.gov/StandardTestCasesFinal6.pdf

Outline of Presentation

- Experiment and Simulation details
- Equilibrium Wall Model description
- Results
  - → Inflow turbulence validation
  - → Qualitative flow features
  - → Comparisons to experiment
- Summary

Experiment Details

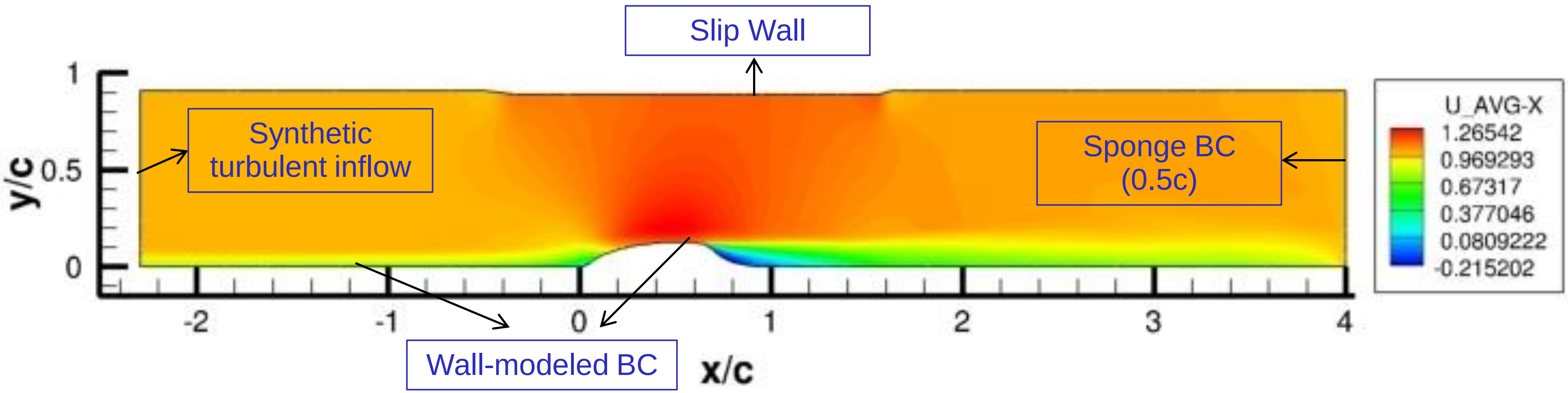


Experimental setup of Greenblatt et al.[1]

- $M_\infty = 0.1$, $Re_c = 929000$
- $Re_\theta \sim 7{,}200$ and $Re_x \sim 4 \times 10^6$ at $x/c = -2.14$
- Hump chord, $c = 420$ mm. Hump height, $h = 53.7$ mm
- Hump model was 584 mm wide (1.39 c) with side-mounted end plates

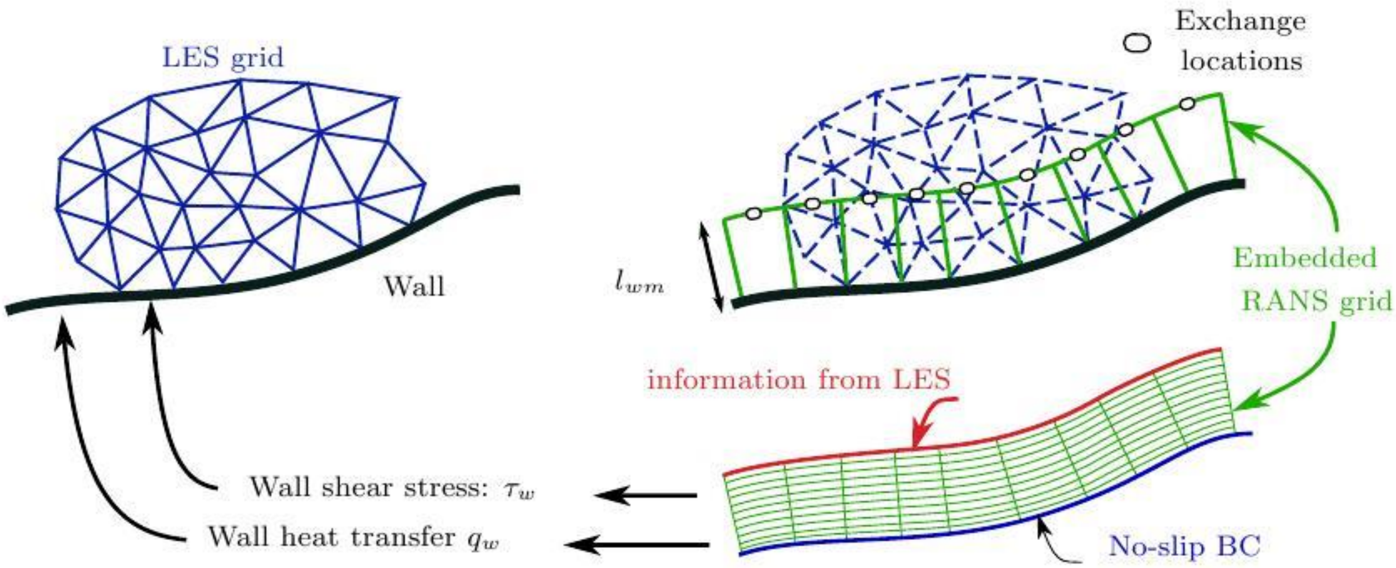
[1] Greenblatt, D., Paschal, K. B., Yao, C. S., Harris, J., Schaeffler, N. W., & Washburn, A. E. (2006). Experimental investigation of separation control part 1: baseline and steady suction. *AIAA journal*, *44*(12), 2820-2830.

Simulation Details



- $M_\infty = 0.1$, $Re_c = 936000$, $Re_\theta \sim 7{,}200$ at x/c = -2.14 matched with experiment.
- Simulations performed using the compressible *Charles* solver from Cascade Technologies.
- 2nd order cell-centered, unstructured finite volume spatial discretization with explicit RK3 time stepping.
- Constant coefficient Vreman SGS model and Equilibrium Wall Model.
- Contoured top wall to account for effect of end plates.
- Small slot at x/c~0.65 of width 4×10^{-3} c not modeled in the current simulations.
- Synthetic method used to specify inflow turbulence.

Equilibrium Wall Model Equations



- Compressible equilibrium BL ODEs solved in WM region.

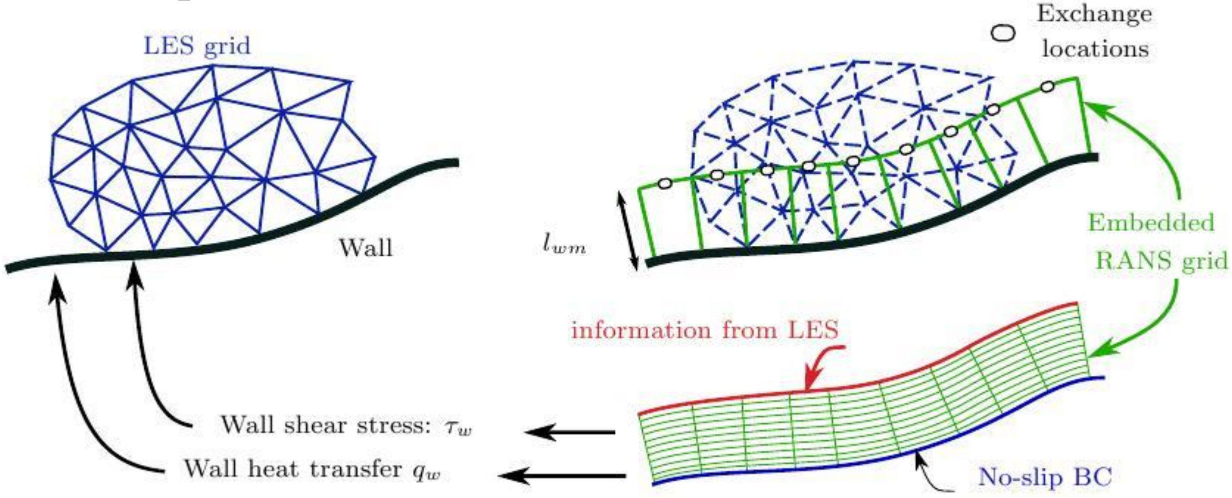
$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}\eta}\left((\mu+\mu_{t,wm})\frac{\mathrm{d}u_{\parallel}}{\mathrm{d}\eta}\right) &= 0\,,\\ \frac{\mathrm{d}}{\mathrm{d}\eta}\left((\mu+\mu_{t,wm})u_{\parallel}\frac{\mathrm{d}u_{\parallel}}{\mathrm{d}\eta}+(\lambda+\lambda_{t,wm})\frac{\mathrm{d}T}{\mathrm{d}\eta}\right) &= 0\,,\end{aligned}$$

- Eddy viscosity obtained from mixing-length model and turbulent thermal conductivity obtained assuming constant Pr_t=0.9.

$$\mu_{t,wm}=\kappa\eta\sqrt{\rho\tau_w}\left[1-\exp\left(-\frac{\eta^+}{A^+}\right)\right]^2\,,\quad \text{with } A^+=17,\ \kappa=0.41\,.$$

[1] Figure taken from : Bodart & Larsson, AIAA-2012-3022.

Equilibrium Wall Model



- Equilibrium Wall Model successfully applied to multi-element airfoil by Bodart & Larsson (AIAA 2012, 2013) and to NASA hump and periodic hill by Park (AIAA 2016, CTR-SP 2014).
- Additional cost: ~10-30% for equilibrium WM. (100-150% for non-equilibrium WM, Park JCP 2016). Also, parallel efficiency sub-optimal for < 50,000 cells/core (Park, JCP 2016).
- Traditionally WMLES uses LES information from the 1st grid point away from the wall.
- Kawai & Larsson (PoF 2012) showed that this could lead to an erroneous wall shear stress prediction for a flat plate boundary layer and using information from the 3rd or away grid point significantly improves results.
- Effect of exchange location in separated flows needs to be examined.

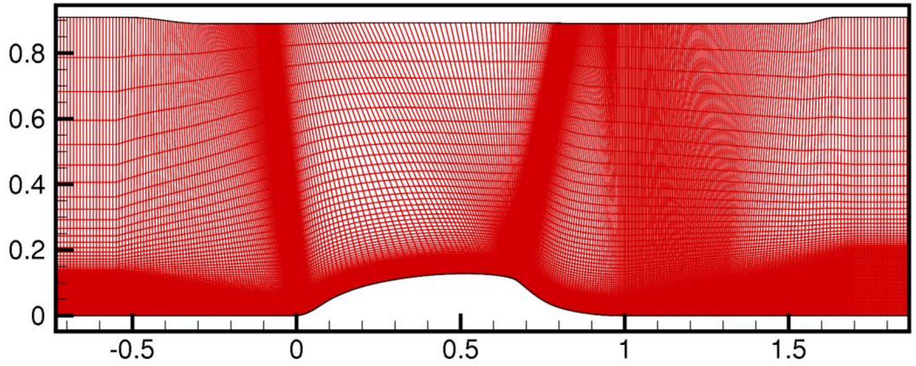
Simulation Details

Case	Grid	Grid points	Inflow plane	Wall Model applied at
cWM1	Coarse	4.4 million	-2.29	1st grid point
cWM3	Coarse	4.4 million	-2.29	3rd grid point
fWM1	Fine	11 million	-3.0	1st grid point
fWM3	Fine	11 million	-3.0	3rd grid point

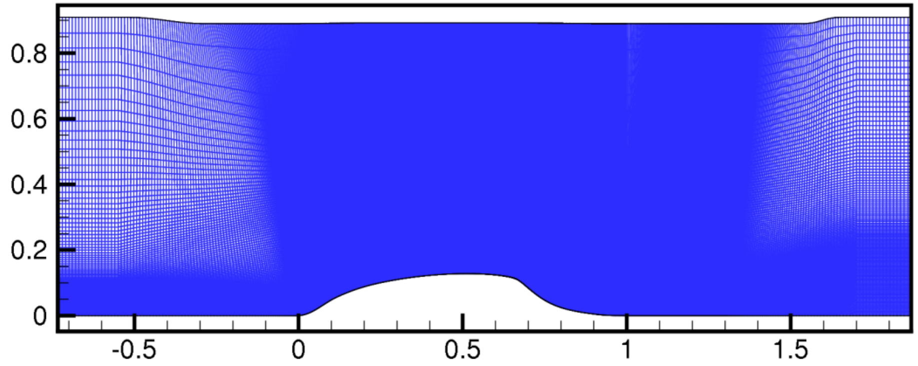
- 4 different simulations performed to study effect of grid resolution and exchange location.
- Spanwise width of the domain = 0.3 c.
- Simulations run for 12-15 c/u_∞ after which statistics were collected for 15 c/u_∞.
- Coarse grid simulations ran in ~ 6 days with 320 cores (Intel Westmere X5675) for 30 c/u_∞ while fine grid took 14 days.
- 3rd grid point of fine grid roughly corresponds to the 1st grid point in the coarse grid.
- Wall-resolved LES calculation for the same domain size would require ~ 400 million grid points for $\Delta x^+ \sim 50$, $\Delta y_{min}^+ \sim 1$ and $\Delta z^+ \sim 25$.

Grid Spacing

Coarse grid



Fine grid

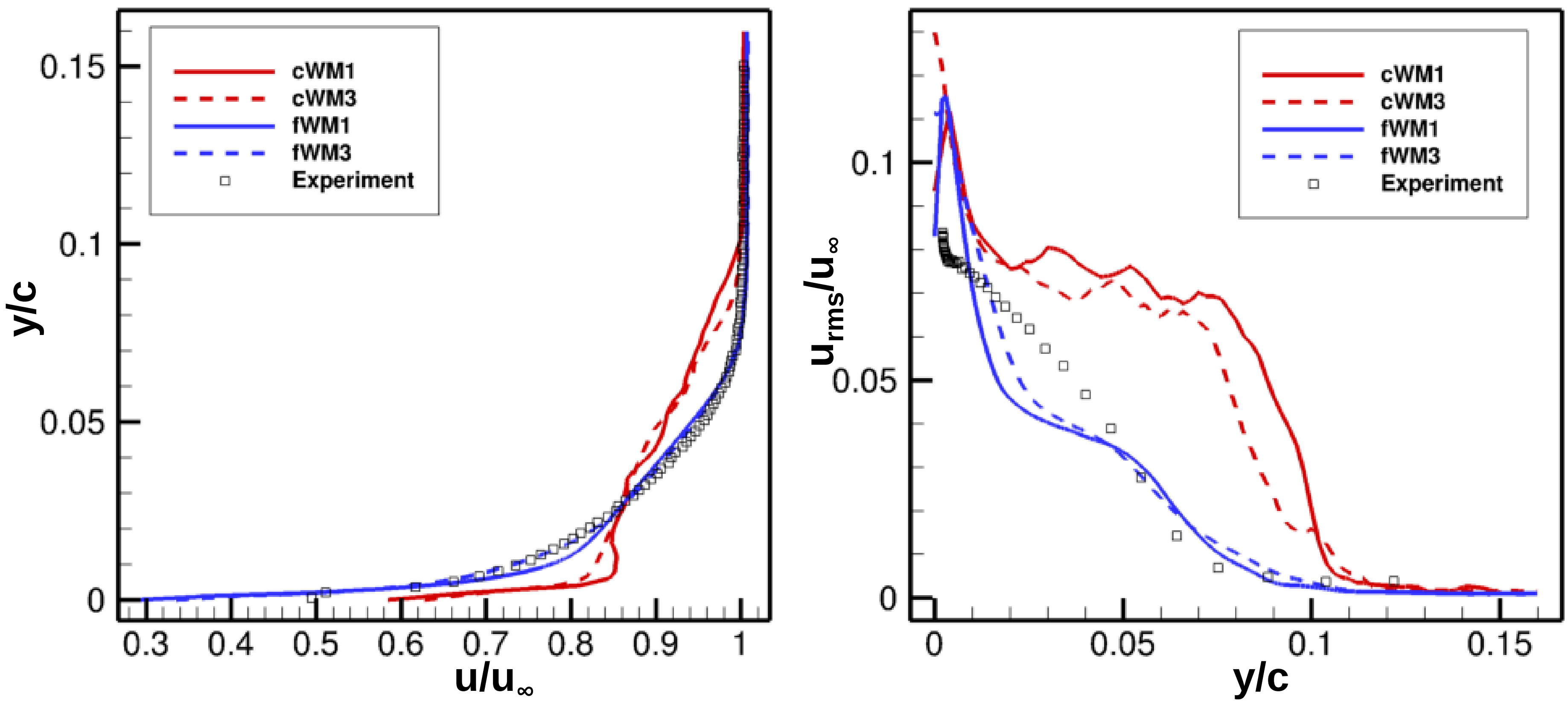


Grid	Region	Δx^+, Δy_{min}^+, Δz^+	δ_{99}/c	n_x/δ, $n_{y,min}/\delta$, n_z/δ
Coarse	-2.29 < x/c < 0	360, 72, 180	0.1	10, 32, 20
	0 < x/c < 1.1	514, 25, 260	0.07	7, 32, 14
	x/c > 1.1	300, 100, 150	0.2	20, 32, 40
Fine	-3 < x/c < 0	360, 36, 180	0.1	10, 32, 20
	0 < x/c < 1.1	77, 10, 260	0.07	46, 32, 14
	x/c > 1.1	300, 100,150	0.2	20, 32, 40

- Coarse grid : 814, 90 and 60 points in x, y and z, 222 points on hump.
  Fine grid : 1377, 140 and 60 points in x, y and z, 771 points on hump.

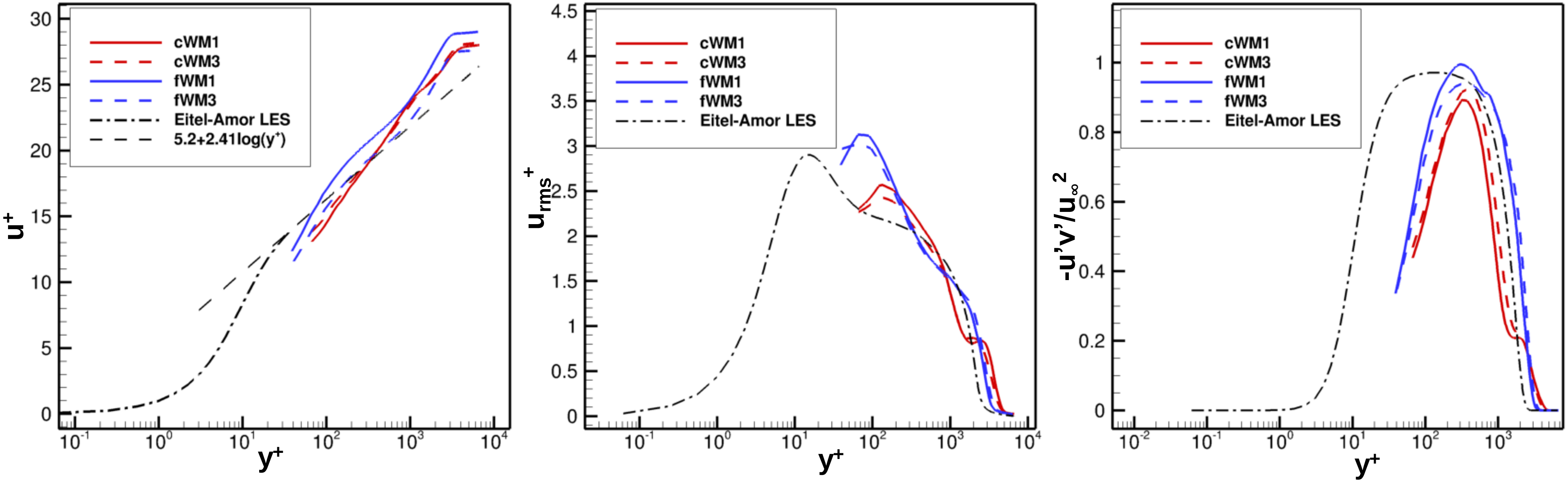
- n_x/δ ~ 5-32, n_y/δ ~ 16-32, n_z/δ ~ 15-32 commonly used in WMLES (Choi & Moin, PoF 2012).

Upstream comparisons to experiment



- Comparison to experiment at x/c=-2.14
- Turbulence not fully developed at this location. Typically ~20δ needed to get fully developed turbulence for synthetic turbulence inflow.
- Distance from inflow ~2δ for coarse grid (inflow at x/c=-2.29) and ~13δ for fine grid (inflow at x/c=-3), hence, better agreement for fine grid

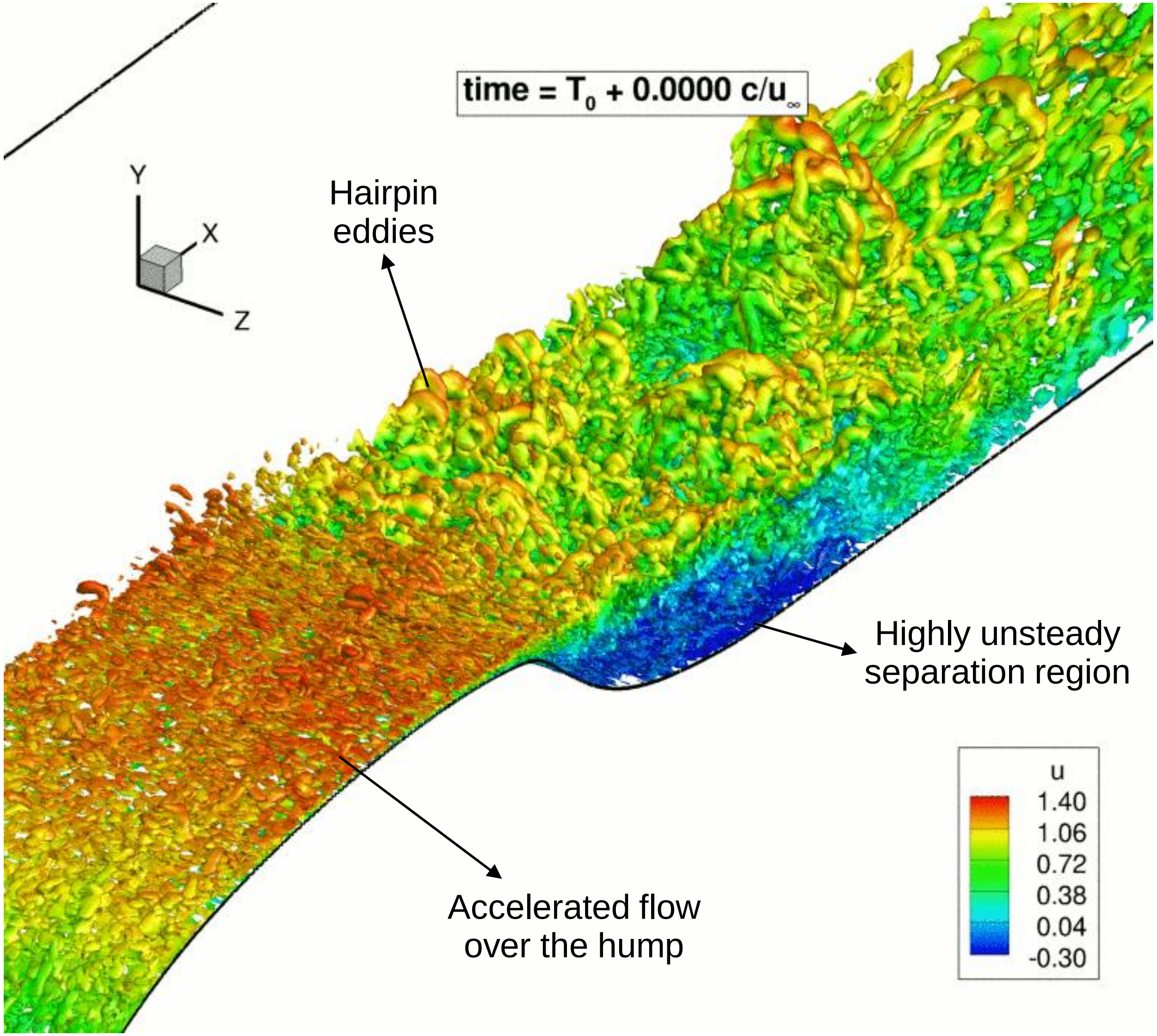
Inflow Turbulence Validation



- Incompressible turbulent boundary layer mean data at Re_θ = 7000 from resolved LES of Eitel-Amor et al.[1] specified at inflow of domain.
- Turbulence statistics at x/c=-0.5 compared to incompressible TBL data at x/c ~ -2.2.
- Reasonable agreement indicating turbulence is fully developed.

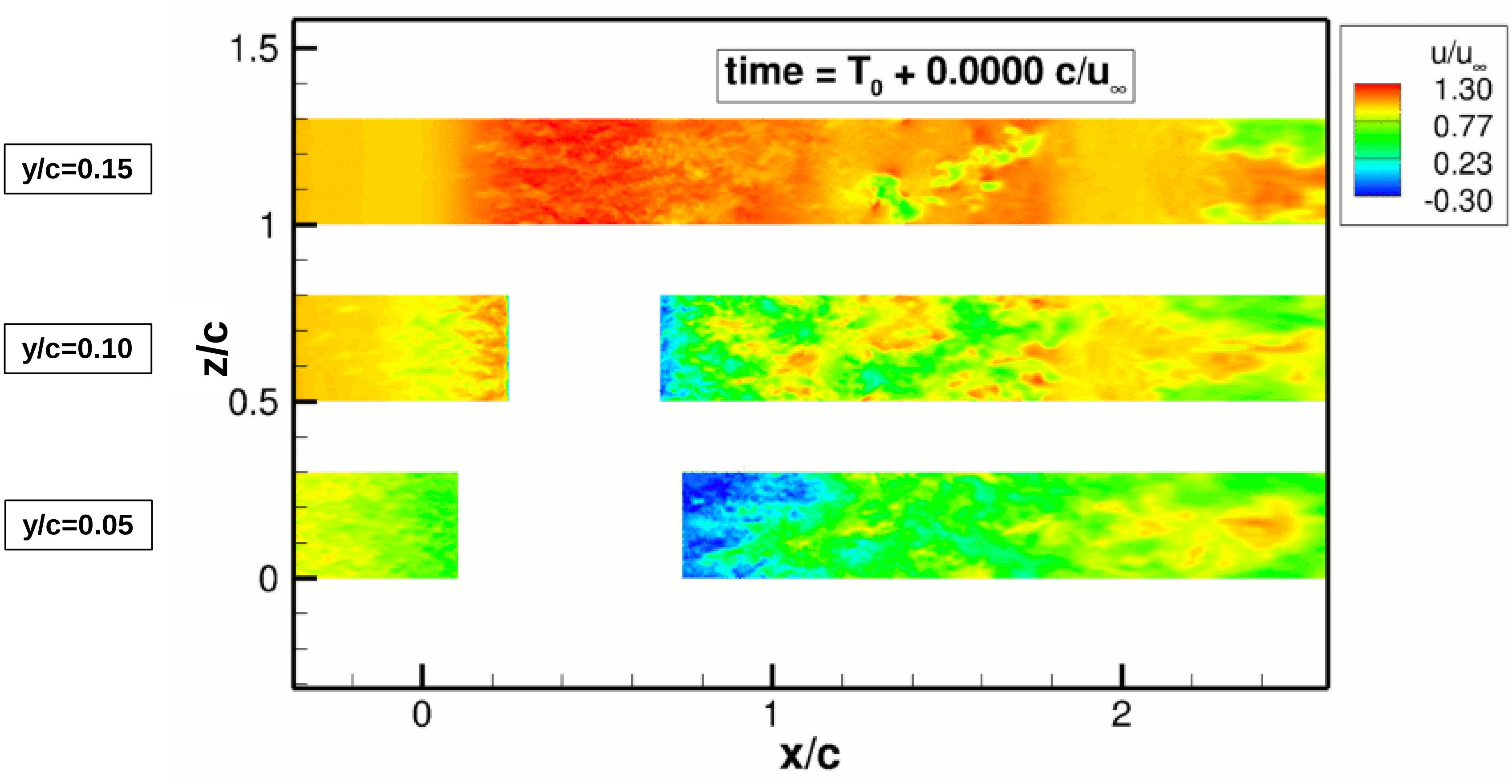
[1] Eitel-Amor, G., Örlü, R., & Schlatter, P. (2014). Simulation and validation of a spatially evolving turbulent boundary layer up to Reθ= 8300. *International Journal of Heat and Fluid Flow*, *47*, 57-69.

Vortical features of the flow



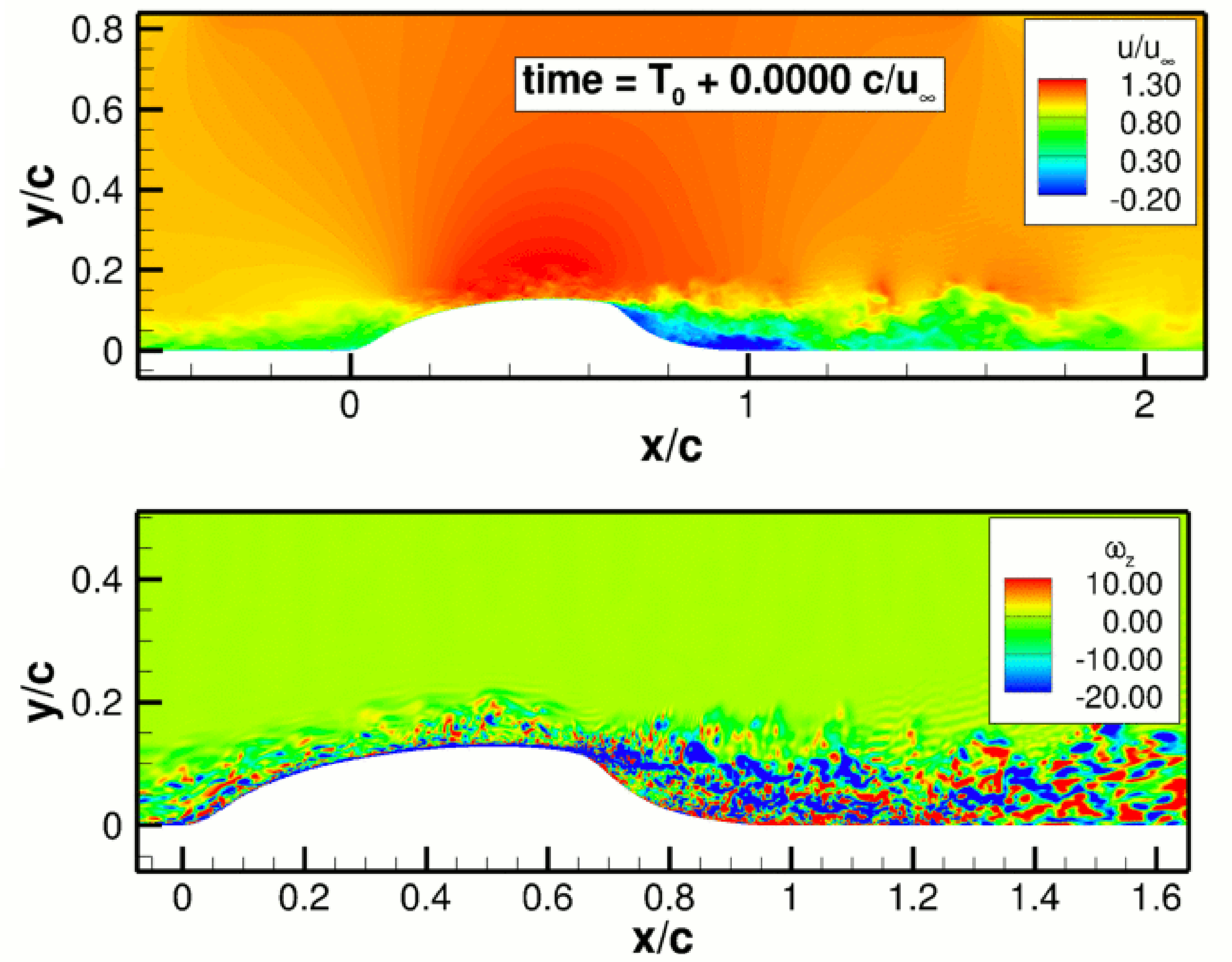
- Iso-contours of Q-criterion colored by instantaneous streamwise velocity to depict vortices for fWM3.
- WMLES captures the hairpin-shaped eddies in the outer layer of the boundary layer.

Top view animation



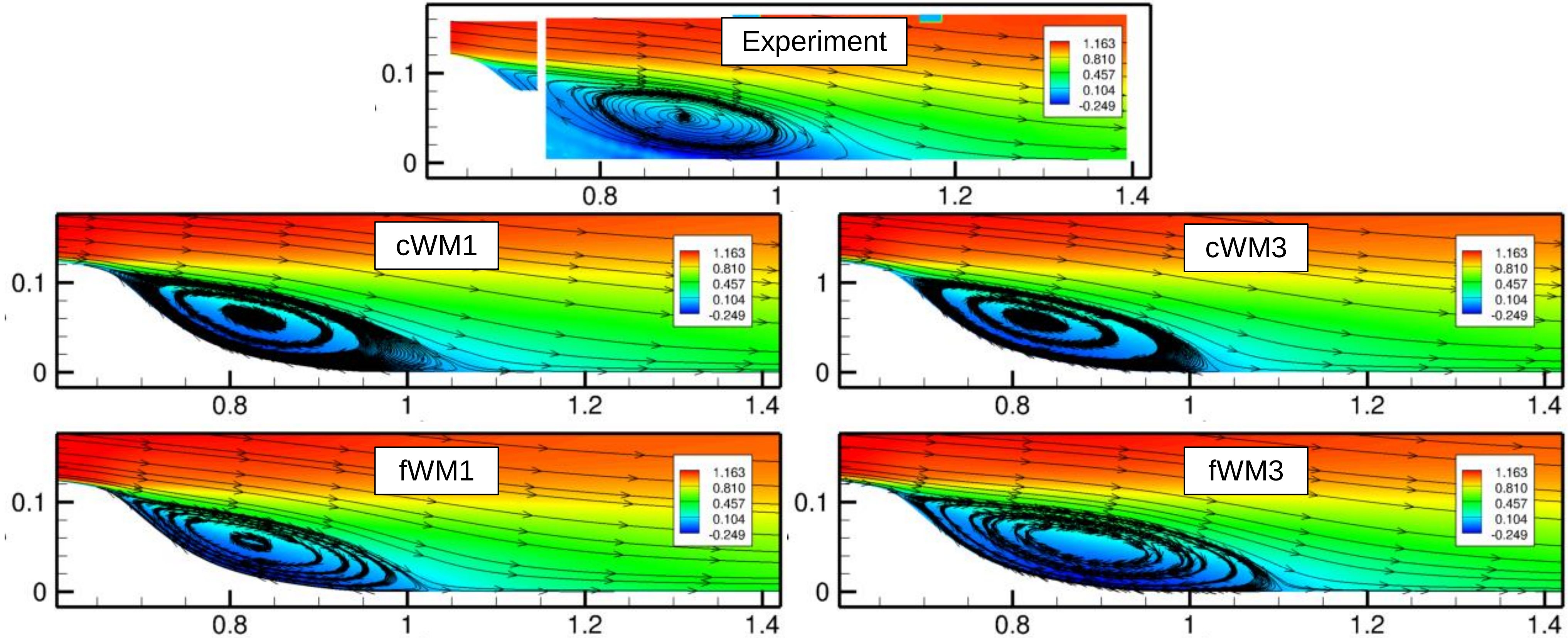
- Instantaneous streamwise velocity contours for fWM3
- Fine scales seen over the hump at y/c=0.15
- Spanwise oscillation of the separated region at y/c=0.05

Side view animation



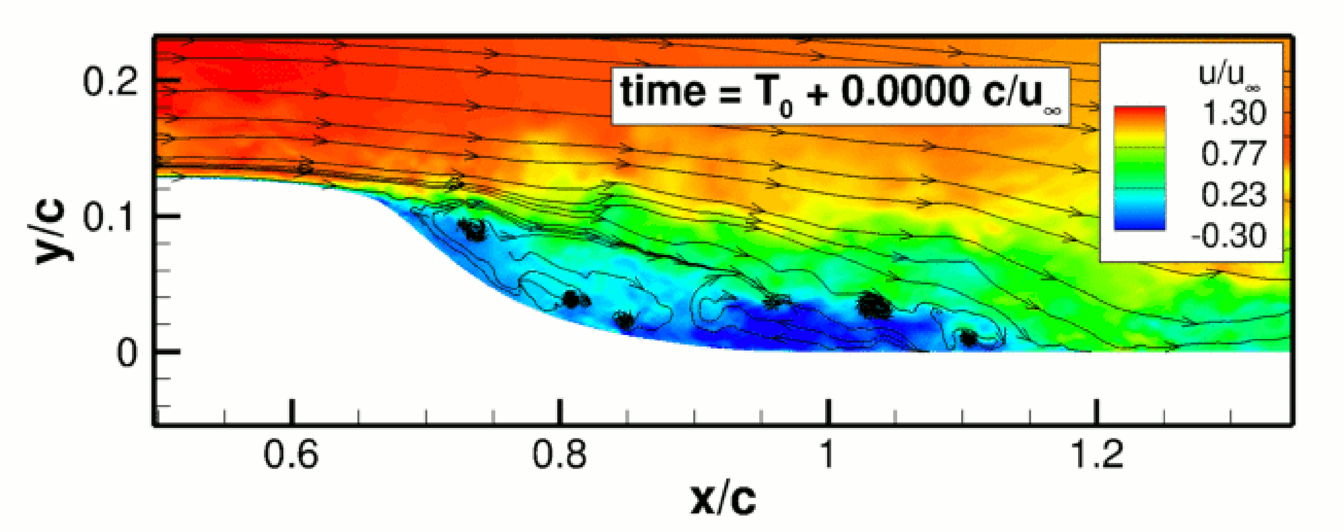
- Instantaneous streamwise velocity and spanwise vorticity contours for fWM3
- Vortices in the boundary layer of the flow over the hump clearly visible
- Flapping of the separation shear layer

Separation Bubble Characteristics



- Qualitatively similar to experiment
- Overall, fine grid simulations with LES information from 3rd grid point agrees best with experiment

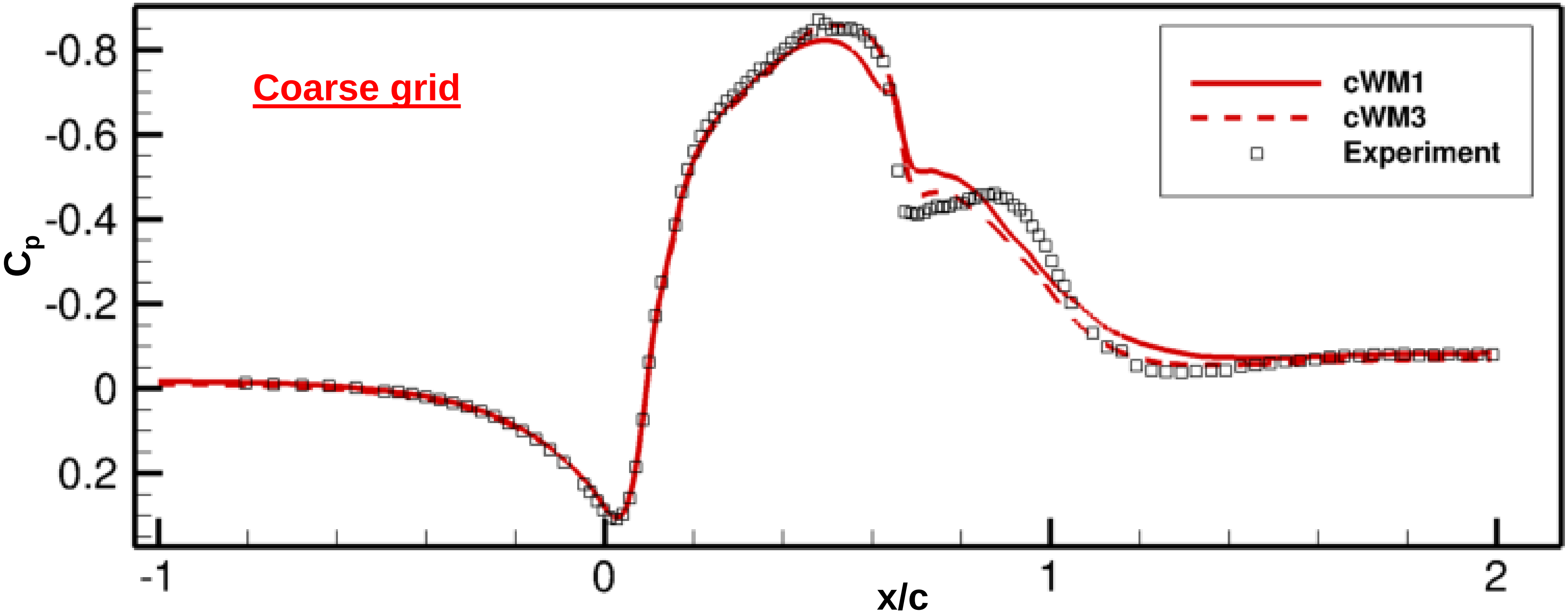
Separation Bubble Characteristics



Case	Separation location (x/c)	Reattachment location (x/c)	Bubble length (Δx/c)	Error in bubble length (%)
Expt.	0.665 ± 0.005	1.10 ± 0.005	0.435	-
cWM1	0.615	1.08	0.465	6.9
cWM3	0.655	1.045	0.39	10.3
fWM1	0.637	1.035	0.398	8.5
fWM3	0.655	1.105	0.45	3.4

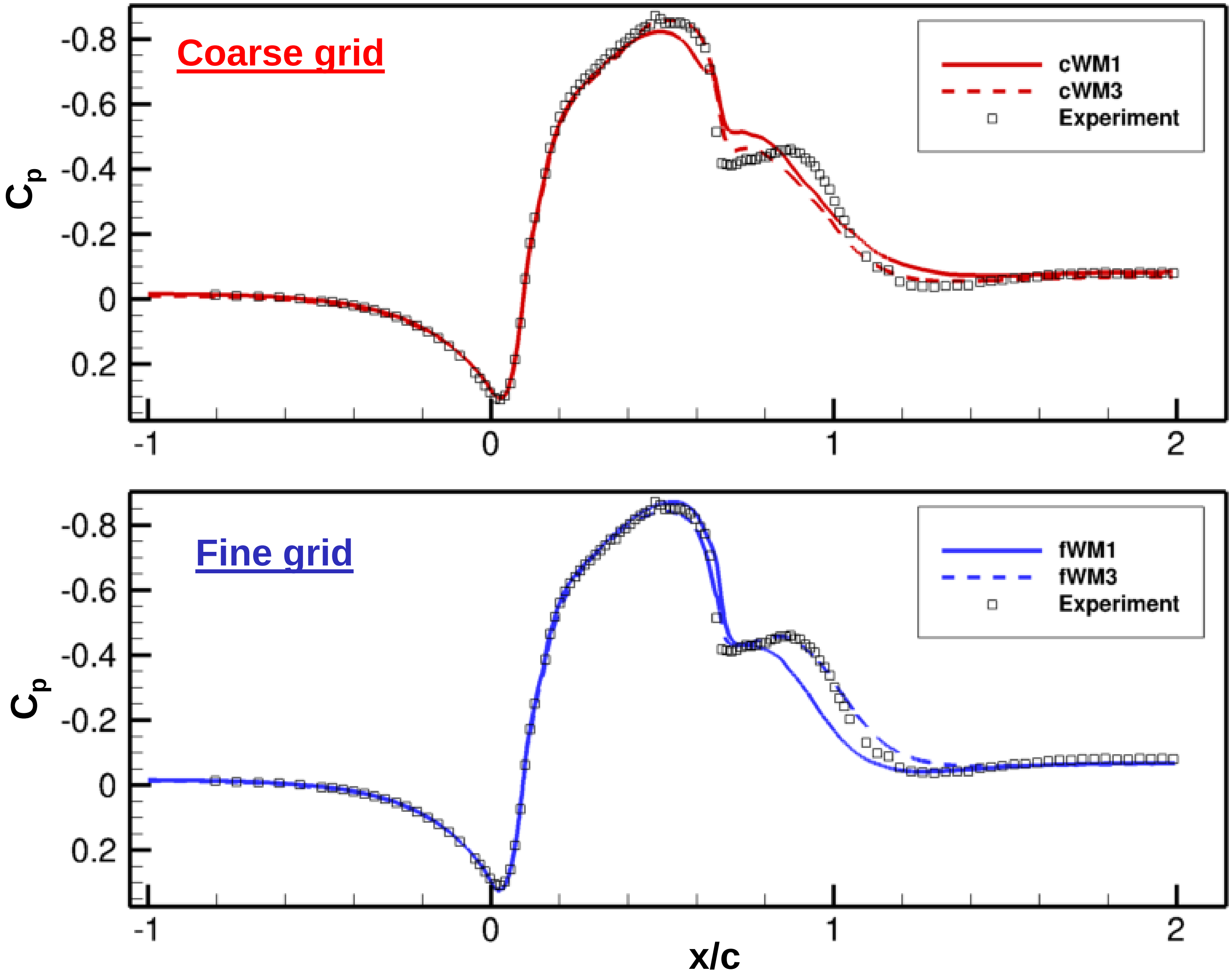
- Separation and reattachment locations reported based on mean streamlines
- fWM3 agrees within 3.4% of the experimental value for bubble length

Wall pressure comparisons



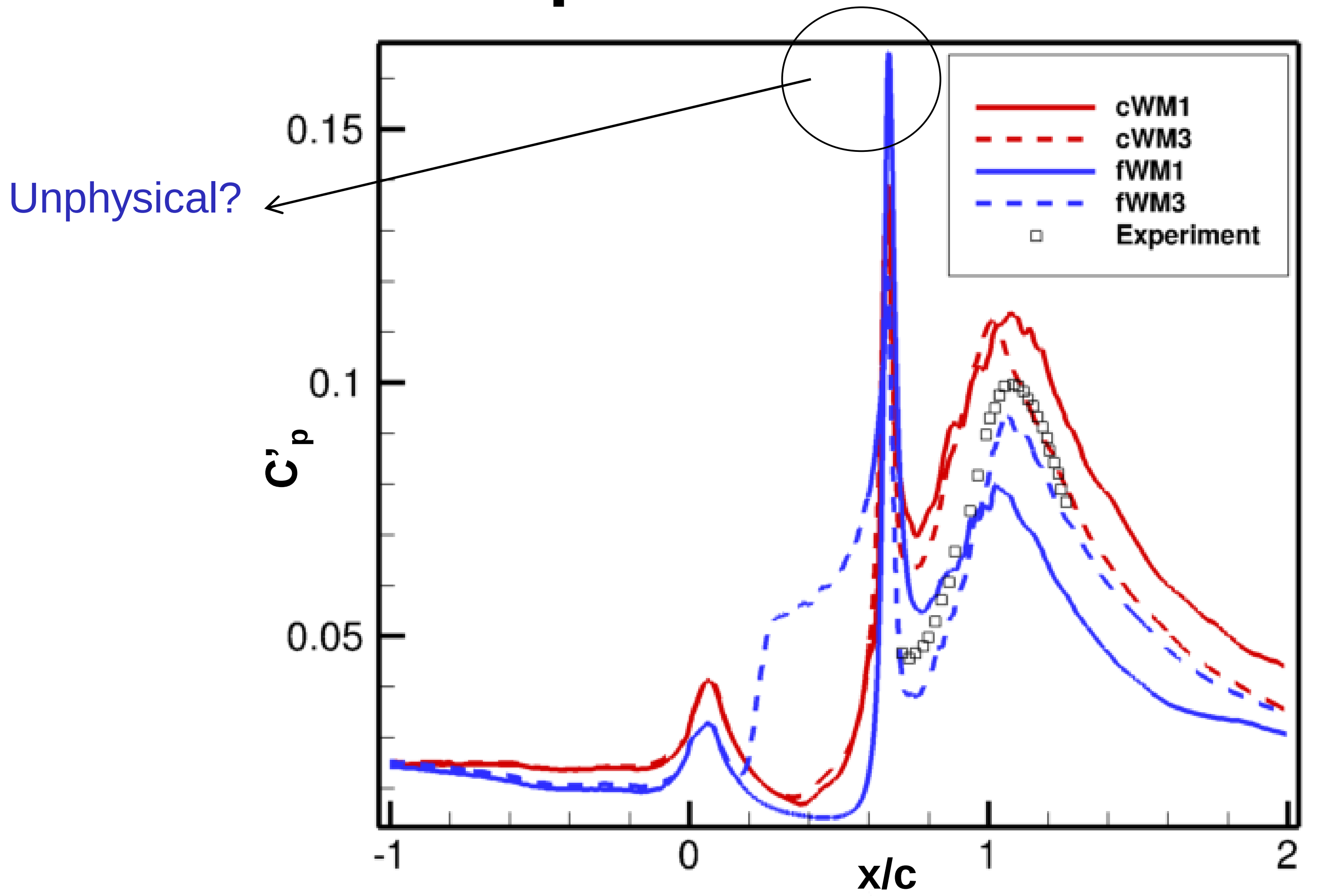
- Reference pressure chosen to match the experimental C_p upstream of the hump.
- Comparison looks reasonable except in the separation region.
- cWM3 closer to experiment but still needs improvement.

Wall pressure comparisons



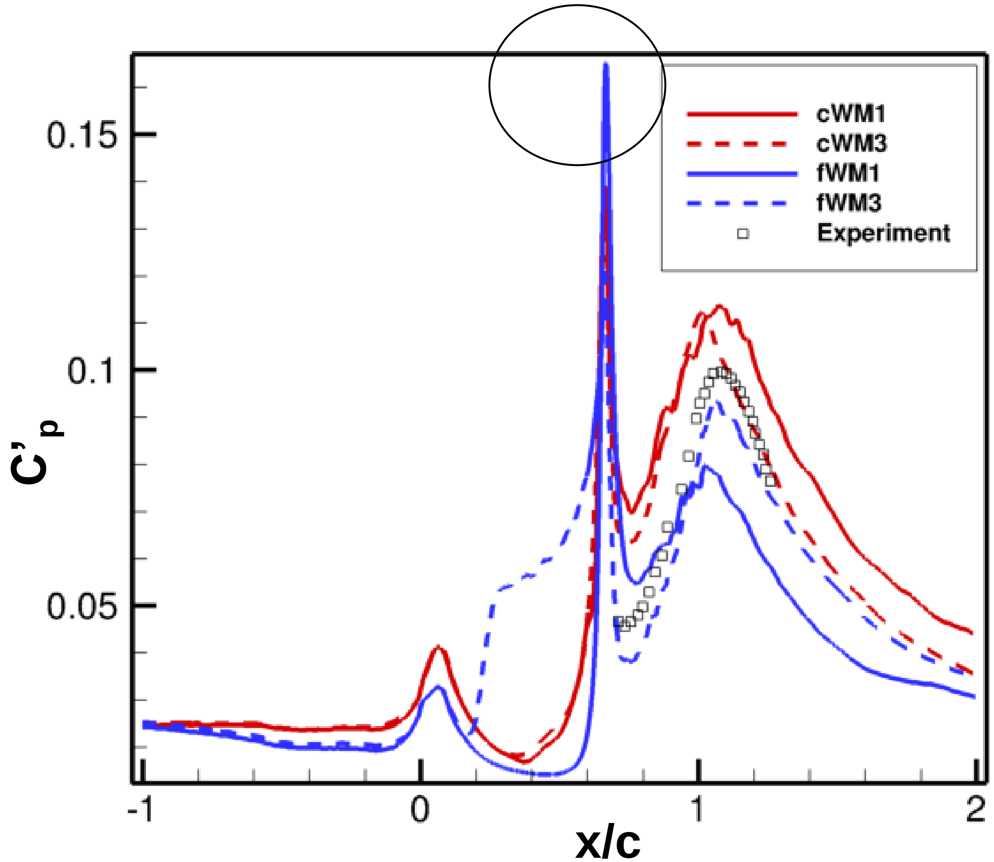
- fWM3 agrees well with experiment.

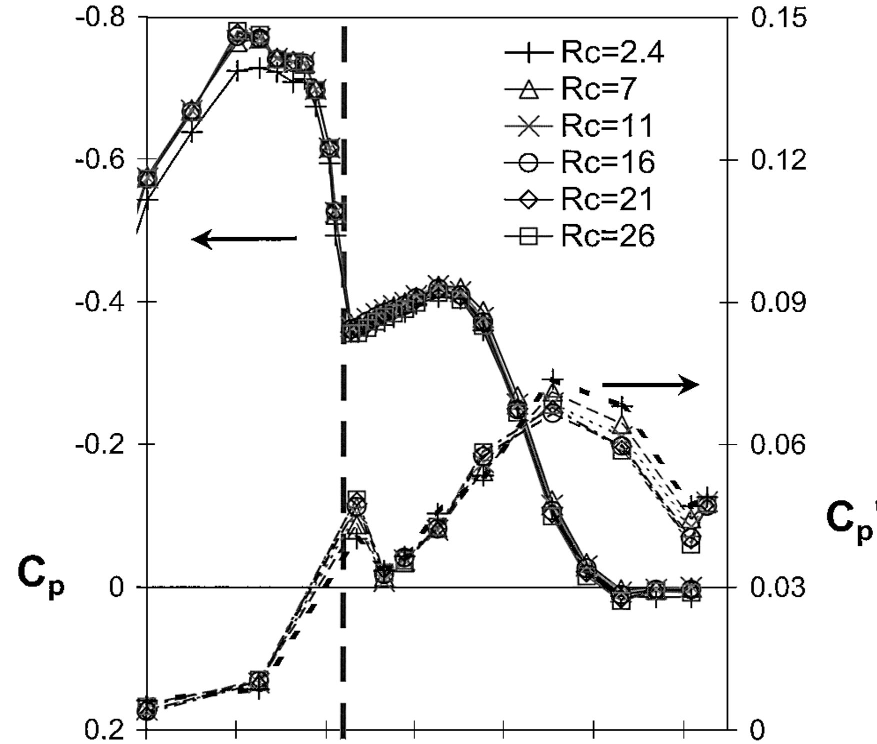
Wall-pressure fluctuations



- All simulations qualitatively agree with experimental data with fWM3 showing good quantitative agreement with experiment.
- Pressure fluctuations higher near separation. Appears to be unphysical based on data from other separated flows. Possible reasons: Grid smoothness.

Wall-pressure fluctuations

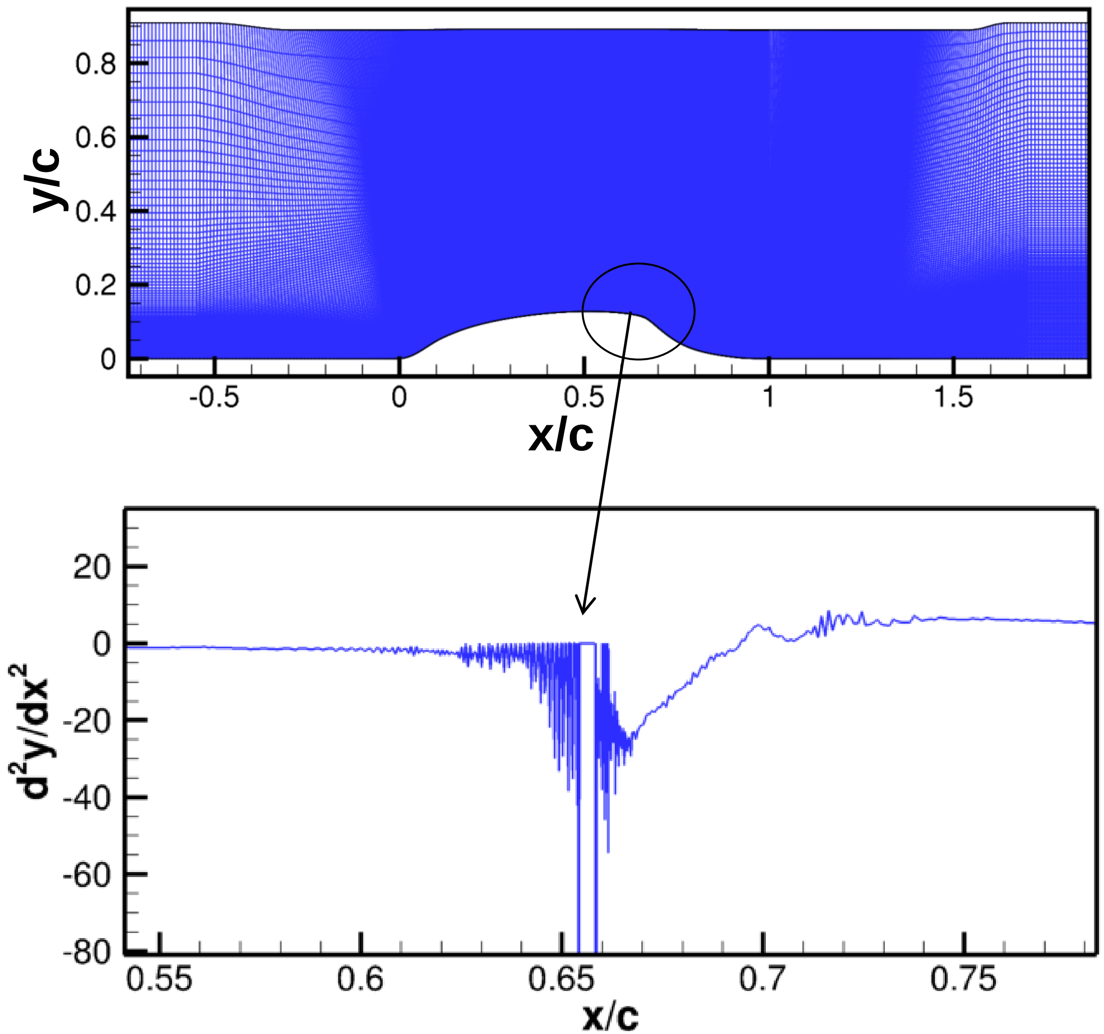


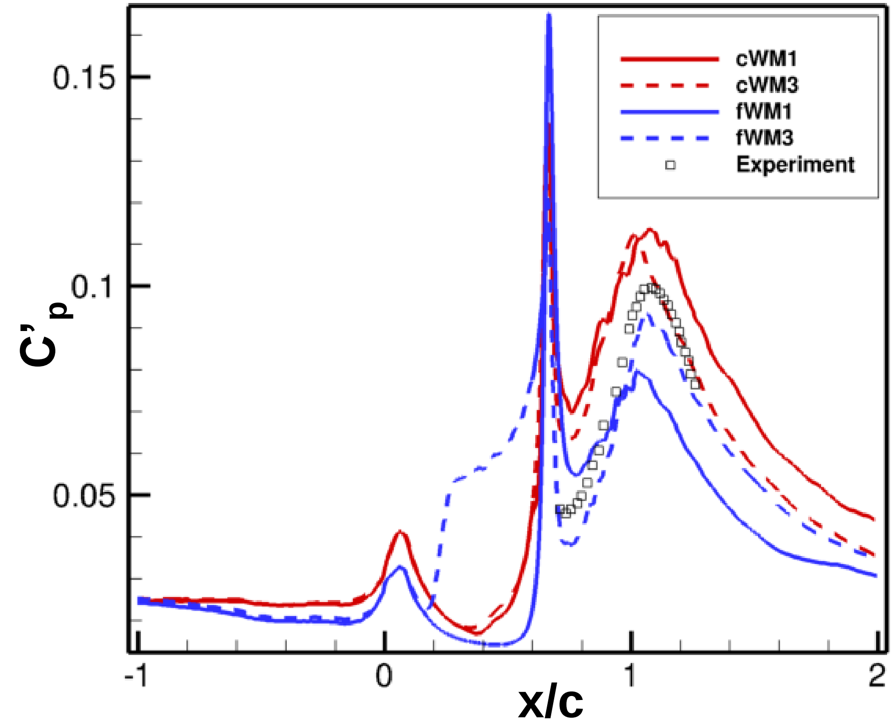


Seifert & Pack, *AIAAJ 2002*

- All simulations qualitatively agree with experimental data with fWM3 showing good quantitative agreement with experiment.
- Pressure fluctuations higher near separation. Appears to be unphysical based on data from other separated flows. Possible reasons: Grid smoothness.

Smoothness of hump geometry

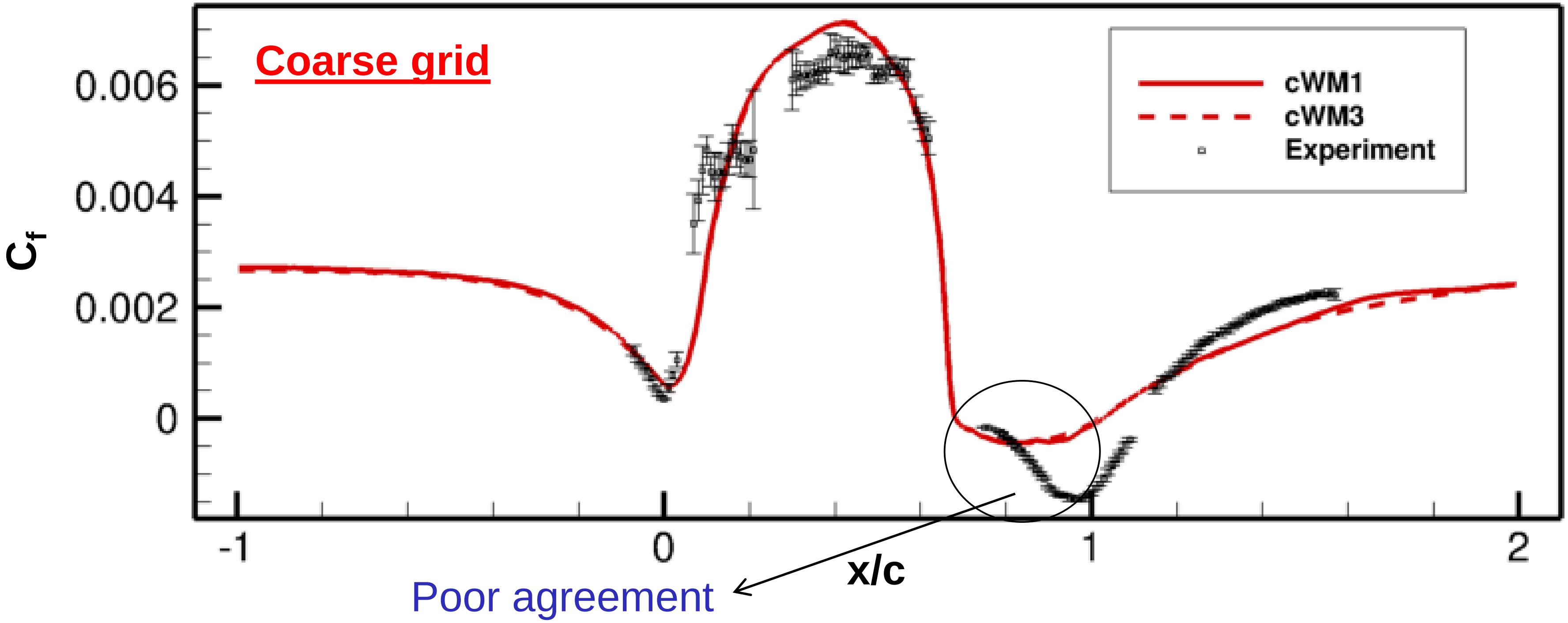




- Non-smoothness of curvature at x/c~0.65 could be responsible for the peak in **C_p'**.
- Similar peak but lower magnitude also observed in resolved LES simulations of Uzun[1].

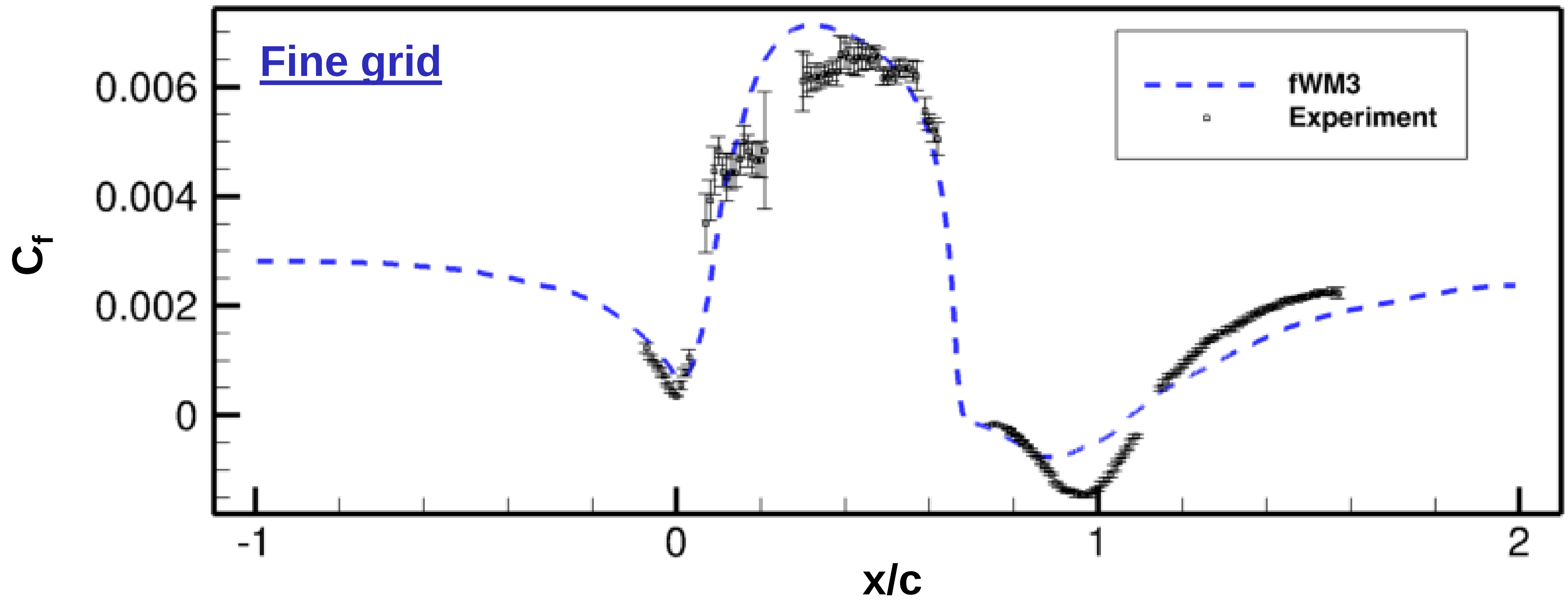
[1]Dr. Ali Uzun, NASA Langley Research Center, Personal Communication.

Wall skin friction comparisons



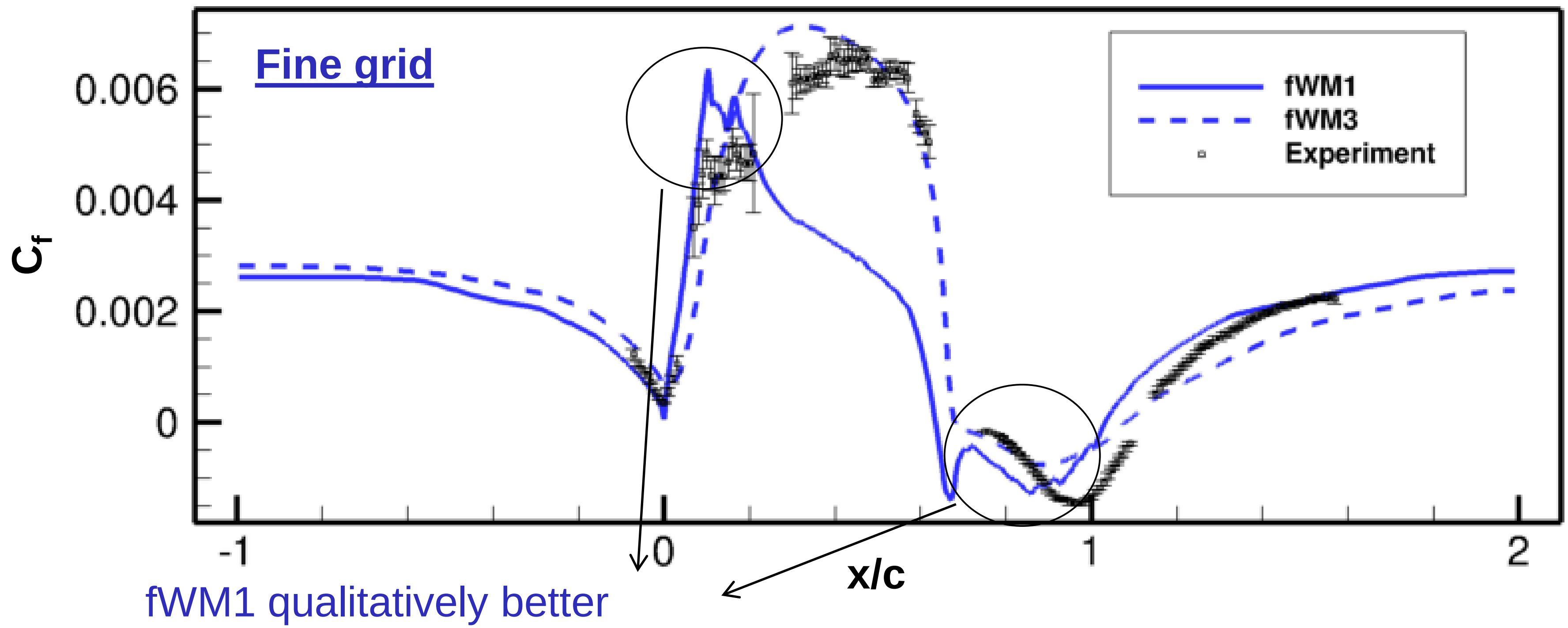
- C_f obtained by averaging wall shear stress obtained from the wall model.
- Reasonable agreement in the attached regions but significant differences in the separated region
- Equilibrium wall model does not account for streamwise gradients.
- Negligible differences in C_f between applying the wall model at the 1st and 3rd grid point for the coarse grid.

Wall skin friction comparisons



- Reasonable agreement in the attached regions but significant differences in the separated region for fWM3

Wall skin friction comparisons

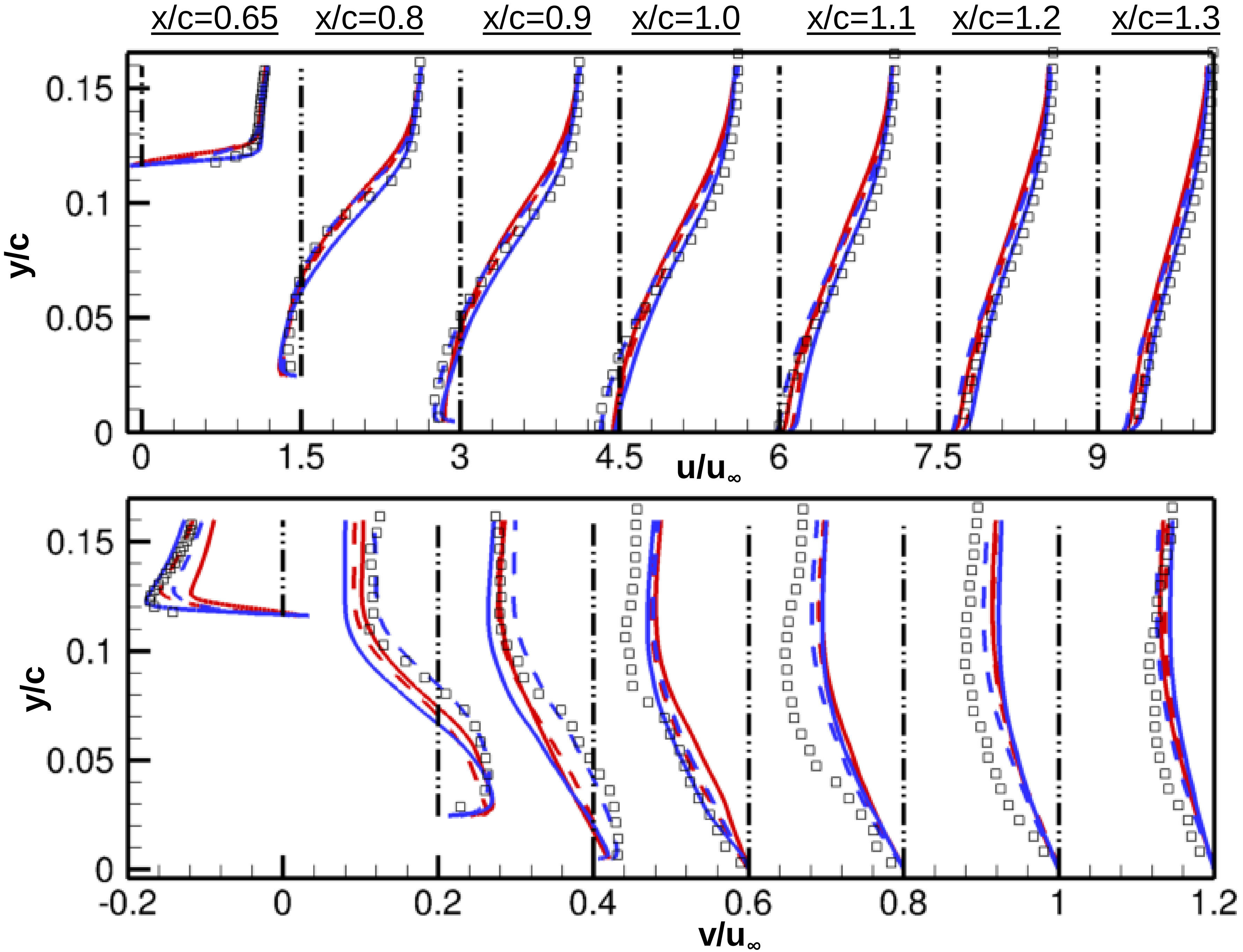


- Reasonable agreement in the attached regions but significant differences in the separated region for fWM3

- fWM1 qualitatively captures the double peak at x/c~0.15 and minimum C_f at x/c~0.8 but severely underpredicts C_f over the hump.

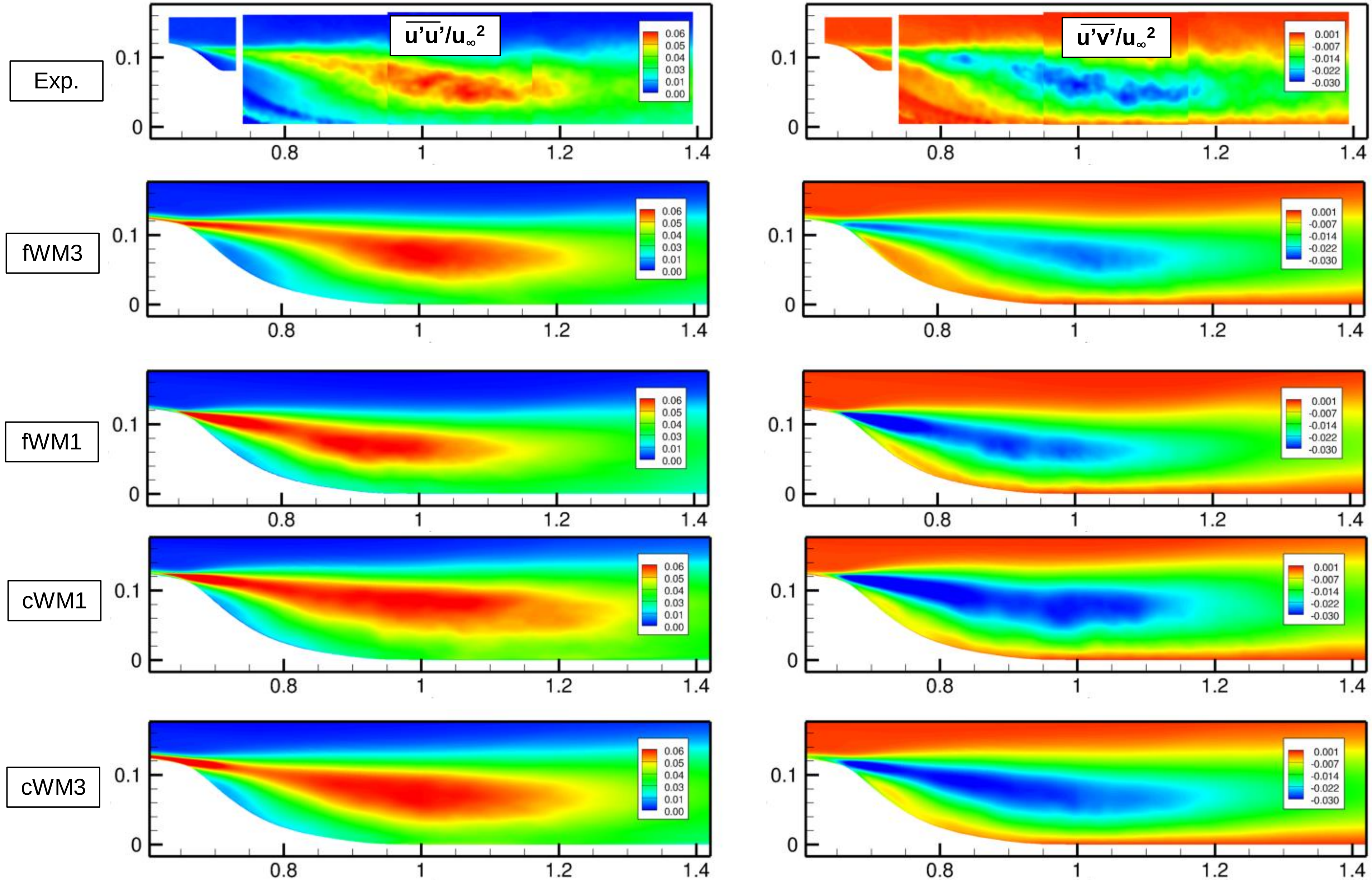
- fWM1 predicts early reattachment as compared to experiment.

Separation region: Velocity comparisons



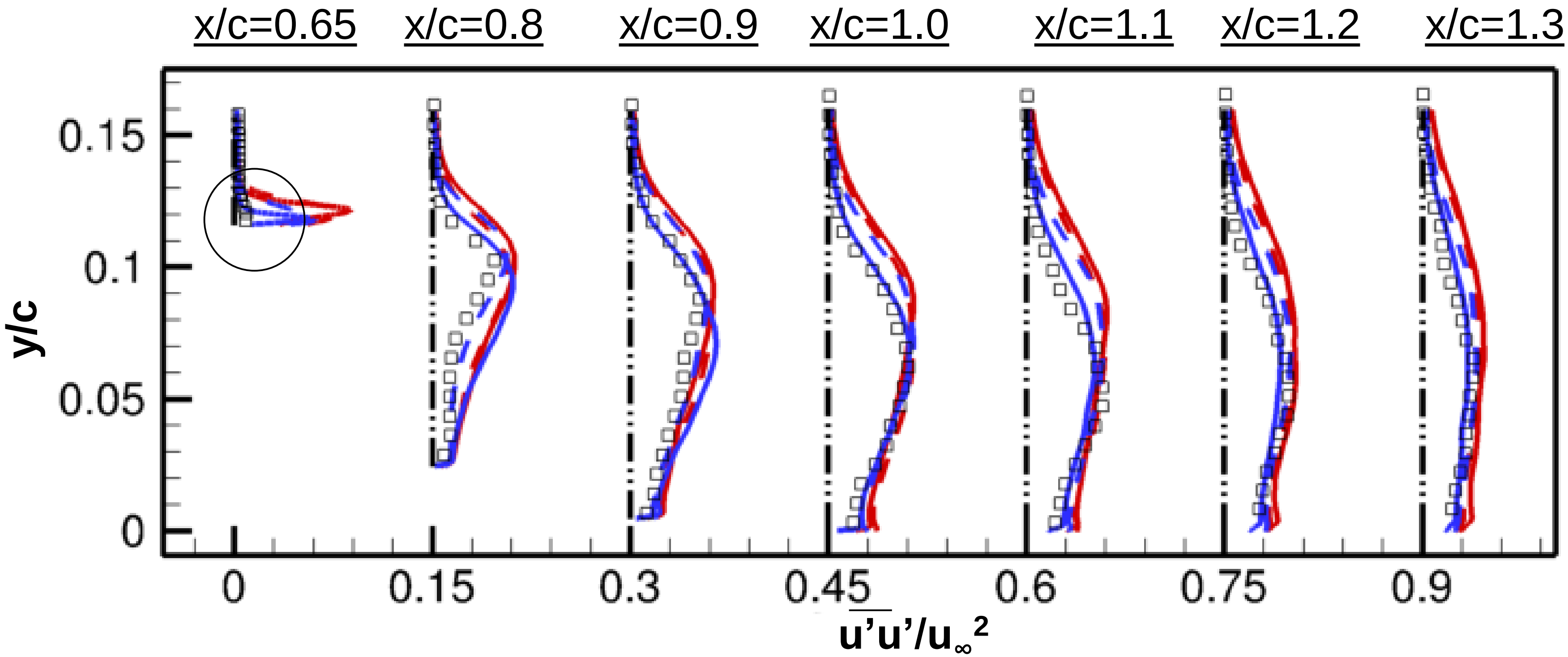
- Legend: Solid red: cWM1, Dashed red: cWM3, Solid blue: fWM1, Dashed blue: fWM3

Separation Bubble Characteristics



- Note the larger unsteadiness near separation in the simulations
- Overall, fWM3 agrees best with experiment.

Separation region: Stress comparisons

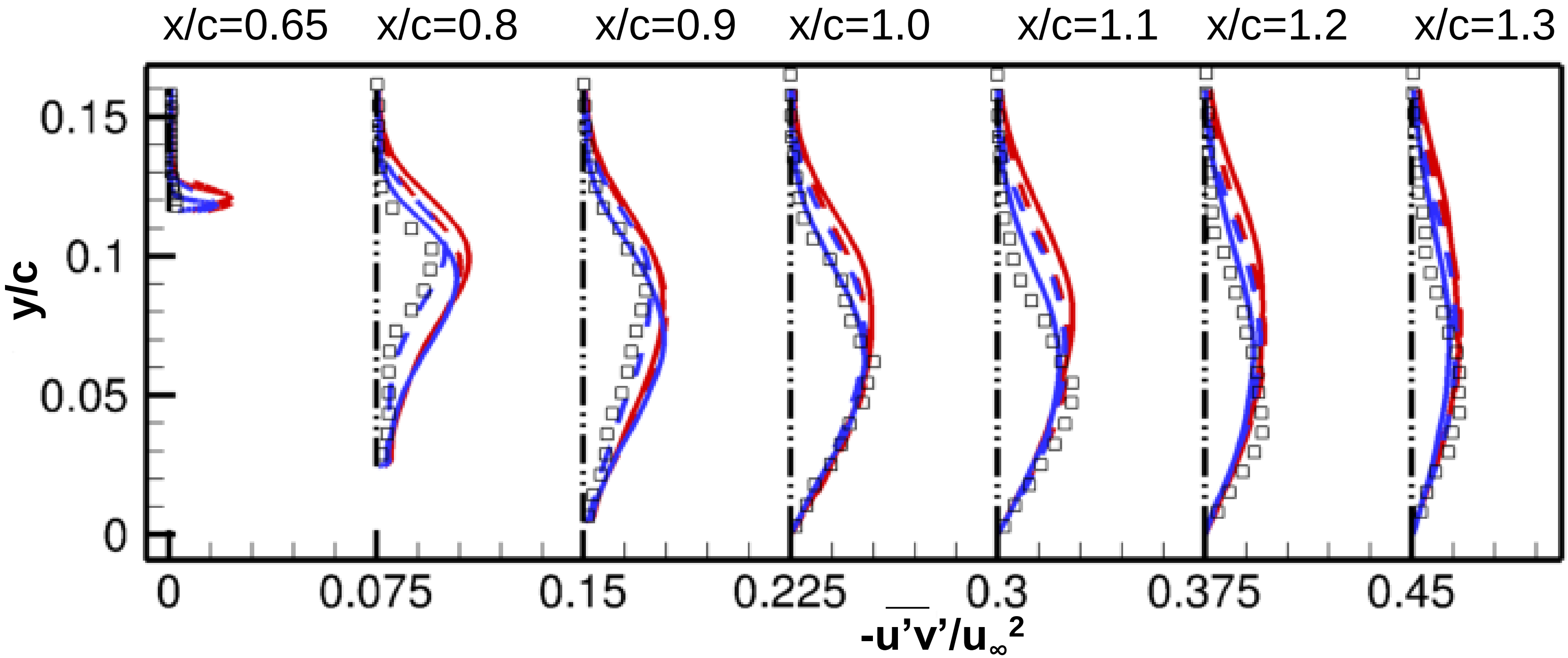


Legend: Solid red: cWM1, Dashed red: cWM3, Solid blue: fWM1, Dashed blue: fWM3

- $\overline{u'u'}$ overpredicted by a factor of 5-6 at x/c=0.65
- Resolved LES of Morgan, Rizzetta & Visbal (2007)[1] also overpredict by a factor of 6 for a lower Re_c = 200,000
- Consistent with peak in C_p' at x/c=0.65

[1]Morgan, P. E., Rizzetta, D. P., & Visbal, M. R. (2007). Large-eddy simulation of separation control for flow over a wall-mounted hump. *AIAA journal*, *45*(11), 2643-2660.

Separation region: Stress comparisons



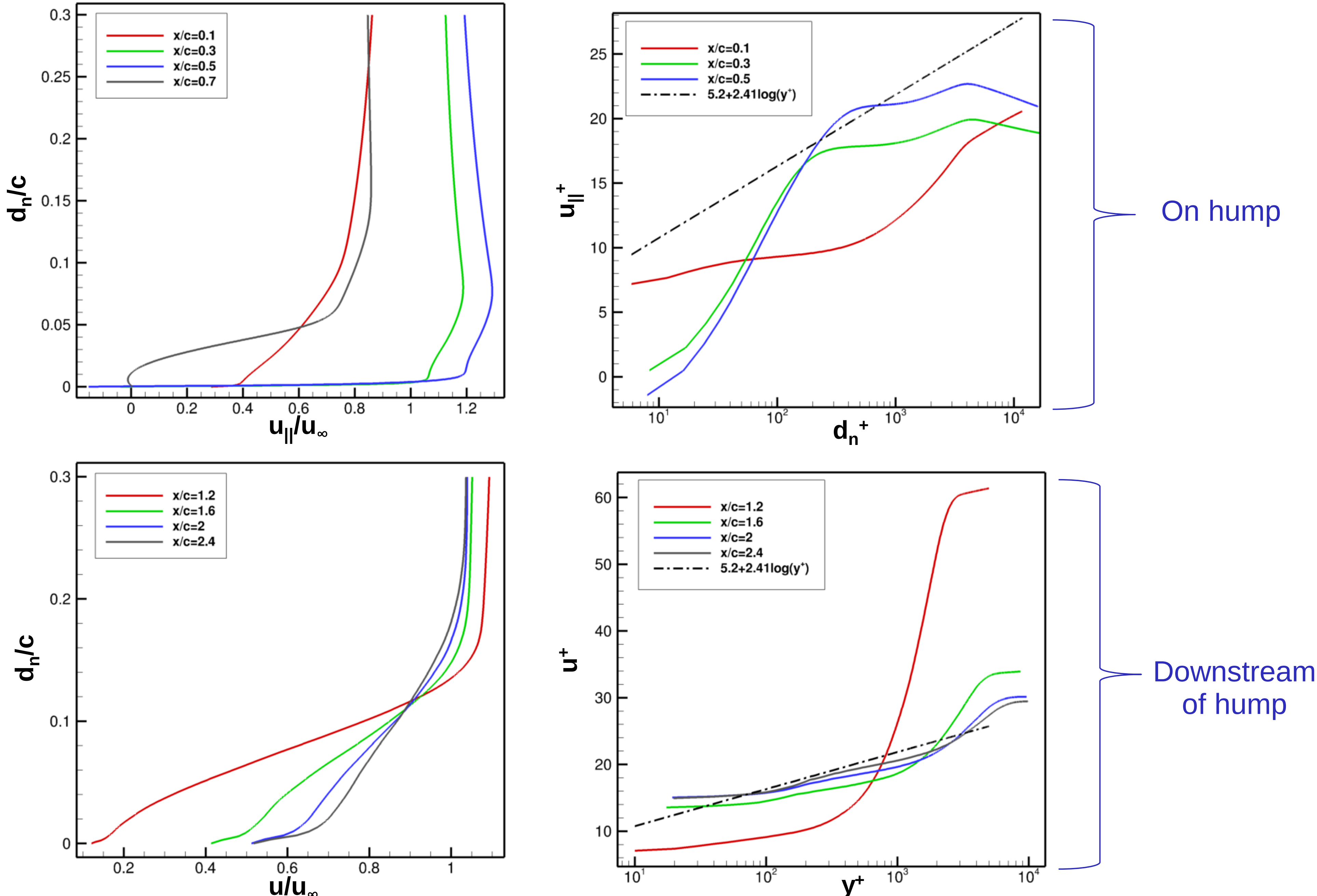
Legend: Solid red: cWM1, Dashed red: cWM3, Solid blue: fWM1, Dashed blue: fWM3

- Reasonable agreement overall
- fWM3 agrees better with experiment near wall while fWM1 agrees better in the upper half of the separation bubble.

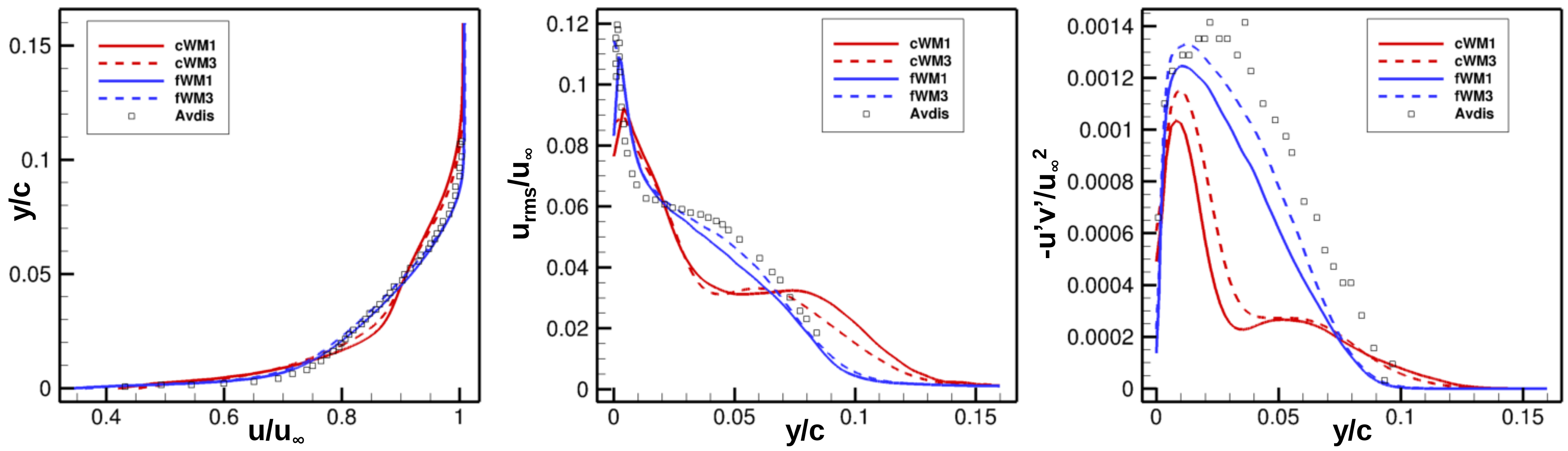
Summary

- Fine grid with exchange location away from the wall gave best agreement with experiments.
- Length of separation bubble predicted within 3.4% of the experimental value.
- Results suggest that WMLES is a promising technique to study high *Re* turbulent flows involving separation at reasonable cost.
- <u>Future Work</u>: Apply WMLES to other problems such as Axisymmetric transonic bump and Juncture flow.

Velocity Profiles on and downstream of the Hump

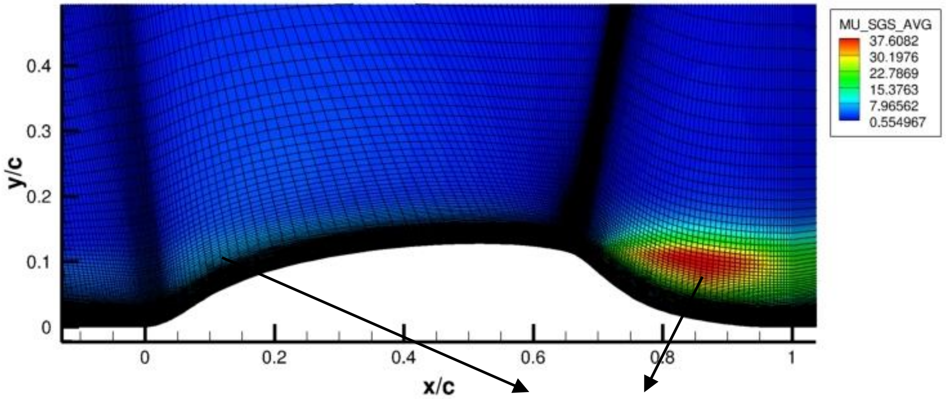


Comparisons to other WMLES data at x/c=-0.81



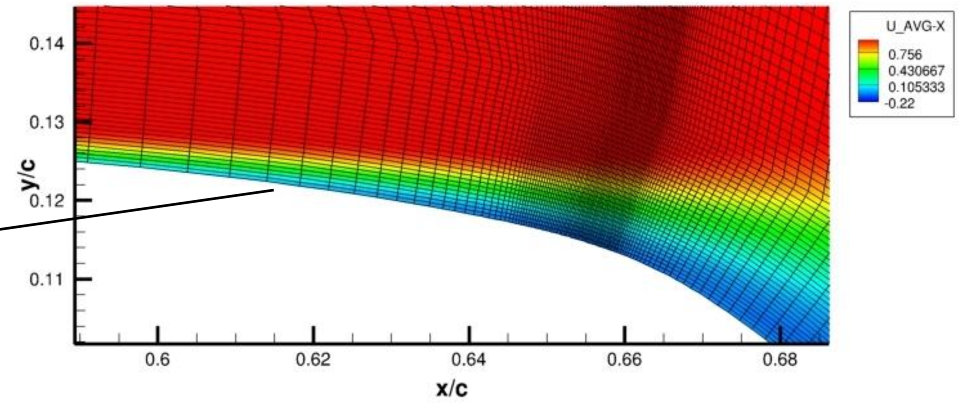
- Comparison to incompressible WMLES of Avdis et al. at x/c=-0.81
- Good agreement between fine grid and Avdis data
- Coarse grid turbulence still not fully developed.
- Some of the differences can be attributed to compressibility effects and the different wall models used.

Possible reasons for discrepancies



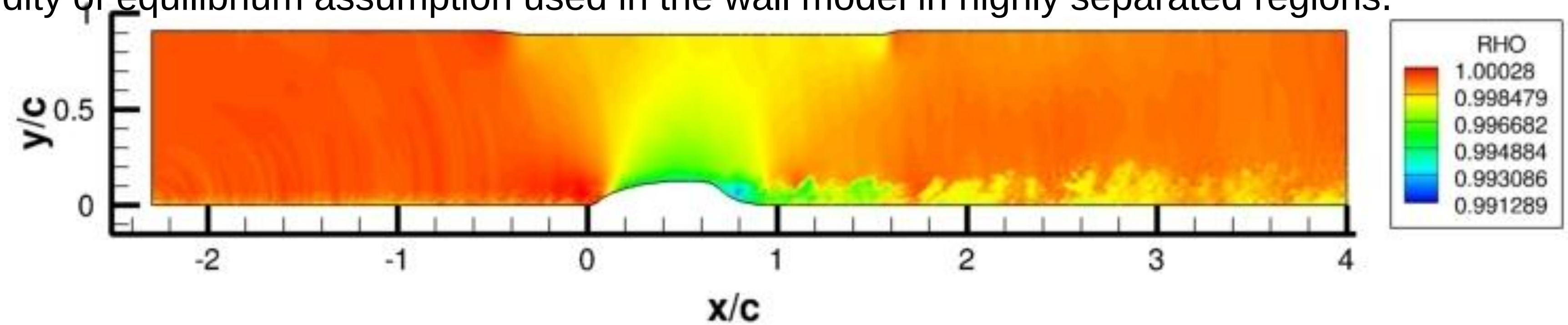
Less resolved regions

- Mean SGS viscosity shown on left indicating regions that are least resolved.
- May require a higher resolution in the wake where SGS viscosity is high.



- Grid too coarse in x.
- Boundary layer on the hump not sufficiently captured in y.

- Other considerations (apart from grid refinement):
  1. VREMAN model (should we use DSM which might perform better in separated regions?)
  2. Inflow turbulence. Is the digital filtering technique good enough?
  3. Validity of equilibrium assumption used in the wall model in highly separated regions.



4. Currently using convective BCs at outflow by prescribing inflow pressure. Change pressure or use sponge BCs at the outflow?